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Asteroseismology of chemically peculiar stars

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Abstract

Pulsational variability is observed in several types of main sequence stars with anomalous chemical abundances. In this contribution I summarize the relationship between pulsations and chemical peculiarities, giving special emphasis to rapid oscillations in magnetic Ap stars. These magneto-acoustic pulsators provide unique opportunities to study the interaction of pulsations, chemical inhomogeneities, and strong magnetic fields. Time-series monitoring of rapidly oscillating Ap stars using high-resolution spectrometers at large telescopes and ultra-precise space photometry has led to a number of important breakthroughs in our understanding of these interesting objects. Interpretation of the roAp frequency spectra has allowed constraining fundamental stellar parameters and probing poorly known properties of the stellar interiors. At the same time, investigation of the pulsational wave propagation in chemically stratified atmospheres of roAp stars has been used as a novel asteroseismic tool to study pulsations as a function of atmospheric height and to map in detail the horizontal structure of the magnetically-distorted p-modes.

Individual Objects: HR 8799, HD 116114, HD 201601 (γ Equ), HD 176232 (10 Aql), HD 134214, HD 137949 (33 Lib), HD 99563, HD 24712, HD 75445, HD 137909 (β CrB), HD 101065, HR 3831.

Introduction

On and near the main sequence, for spectral types from B to early F, one finds a remarkable diversity of the stellar surface properties and variability. In cooler and hotter parts of the H-R diagram a single, powerful process, such as convection in solar-type stars or mass loss in hot massive stars, dominates the physics of stellar atmospheres. In contrast, several processes of comparable magnitude compete in the A-star atmospheres and envelopes, creating interesting and heterogeneous stellar population. The radiative diffusion (Michaud 1970) is the most important process responsible for non-solar surface chemical composition. The diffusion theory suggests that ions heavier than hydrogen are able to levitate or sink under competing influence of the radiation pressure and gravity. Element segregation by the radiative diffusion is easily wiped out by various hydrodynamical mixing effects and, thus, requires a star which is stable over significant part of its outer envelope. Slowly rotating B-F stars with shallow convection zones provide the required stability. The presence of strong, global magnetic field contributes further to the suppression of turbulence and leads to different diffusion velocities depending on the field inclination and strength. Chemically peculiar stars are separated into the two distinct sequences according to their magnetic properties. Am, λ Boo, HgMn stars lack strong magnetic fields and show mild chemical anomalies in chemically homogeneous outer stellar layers. Ap and Bp stars have magnetic fields exceeding few hundred gauss, exhibit extreme chemical anomalies and have substantial vertical and horizontal chemical gradients in the photosphere.

Stellar variability, including pulsations, adds important time-dependent aspect to the complex picture of chemically peculiar B–F stars. Depending on the pulsation frequency and the physics of the interaction between mode excitation, composition gradients and magnetic field, different types of pulsations are suppressed or excited. Observation and asteroseismic interpretation of this pulsational variability is a powerful tool for determining fundamental stellar parameters and constraining poorly known interior properties of chemically peculiar stars.

In this review I summarize our current understanding of the relationship between stellar pulsations and chemical peculiarity for stars in the roAp, δ Scuti, SPB and β Cephei instability regions.

Metallic line A stars

There is near-exclusion of δ Scuti pulsations and Am-type chemical peculiarity (e.g., Breger 1970). The diffusion theory explains this by invoking gravitational settling, which removes He from the He II ionization zone, suppressing the driving of δ Scuti pulsations. When the Am star evolves off the main sequence, the He II ionization region shifts deeper into the star and reaches layers where some residual He is left. This allows excitation of low-amplitude δ Scuti pulsations (Cox et al. 1979). These evolved δ Scuti variables with residual Am-like chemical peculiarities are known as ρ Pup stars.

Classical δ Scuti pulsations have been also claimed in several unevolved Am and Ap stars (e.g., Kurtz 1989; Martinez et al. 1999; González et al. 2008). In some of these cases the detection of pulsational variability is convincing. However, the Ap or Am nature of the stars in question, inferred from photometry and old low-resolution classification spectra, is very uncertain. Detailed model atmosphere and abundance analyses using modern, high-quality spectroscopic material are required to confirm or refute the suspected unusual combination of high-amplitude δ Scuti pulsation and large chemical peculiarities.

Pulsating λ Bootis stars

λ Boo stars are Population I early-A to early-F type stars which exhibit significant underabundance of most iron-peak and heavy elements but show solar abundances of CNO and some other light elements (Paunzen et al. 2002a; Heiter 2002). These chemical properties are believed to arise from contamination of the shallow stellar surface convection zones by the accretion of metal-depleted gas from a circumstellar shell (Venn & Lambert 1990) or a diffuse interstellar cloud (Kamp & Paunzen 2002).

The H-R diagram position of the λ Boo group members partially overlaps with the δ Scuti instability strip. While accumulation of metals and He depletion prevents δ Scuti type pulsations in most Ap and Am stars, the opposite abundance signatures of λ Boo stars make them more promising targets for pulsational observations. In particular, asteroseismic investigations of these stars are interesting for constraining the stellar fundamental parameters and determining the average metal content of the stellar interiors.

High-resolution time-series spectroscopy by Bohlender et al. (1999) revealed the presence of high-degree non-radial pulsations in the majority of investigated λ Boo stars. The overall pulsational characteristics of the group were summarized by Paunzen et al. (2002b). They concluded that the fraction of pulsating λ Boo stars inside the δ Scuti instability strip (at least 70%) is significantly larger than for normal stars. Moreover, in contrast to classical δ Scuti stars, which often pulsate in the fundamental mode, λ Boo stars tend to pulsate in high-overtone modes.

Interestingly, at least one object with λ Boo chemical characteristics – the planetary host star HR 8799 – is known to exhibit the γ Dor type pulsational variability (Zerbi et al. 1999; Gray & Kaye 1999). However, HR 8799 appears to be an exception as other members of the γ Dor group show normal abundance pattern (Bruntt et al. 2008).

Pulsations and chemical peculiarity in hot stars

The hot pulsating stars (Slowly Pulsating B and β Cephei), chemically peculiar Bp stars, and non-pulsating normal B stars coexist in the same part of the H-R diagram (Briquet et al. 2007). Nevertheless, up to now no conclusive evidence for the significant overlap of the pulsational, magnetic, and chemical peculiarity phenomena has been identified for B-type stars. Analysis of the low-resolution UV flux distributions showed that metallicities of SPB (Niemczura 2003) and β Cephei (Niemczura & Daszynska-Daszkiewicz 2005) pulsators do not differ from those of normal B stars. On the other hand, Morel et al. (2008) suggested the existence of a population of nitrogen-rich and boron-depleted slowly rotating B stars based on NLTE abundance analysis of high-resolution spectra. It is possible that the photospheric chemistry of these objects is altered by a weak magnetic field in qualitatively the same way as much stronger fields of Bp stars lead to prominent deviations from the solar chemical composition. However, apart from a small number of SPB and β Cephei stars with $\sim$100 G fields (Neiner et al. 2003; Hubrig et al. 2006a),

the universal presence of weak magnetic fields could not be convincingly established for normal and/or pulsating B-type stars.

The non-magnetic HgMn chemically peculiar stars present another challenge for our understanding of the excitation of pulsations in hot stars. Many HgMn stars are situated within the SPB instability strip. Furthermore, an increased opacity due to accumulation of metals by radiative diffusion in HgMn stars is expected to enhance the driving of the SPB pulsations (Turcotte & Richard 2002). Contrary to this theoretical prediction photometric observations show no evidence of pulsational variability in HgMn stars (Adelman 1998). Spectroscopic line profile variations detected for a handful of HgMn stars is limited to lines of 2–3 heavy elements and is, consequently, attributed to chemical inhomogeneities rather than pulsation (Adelman et al. 2002; Kochukhov et al. 2005; Hubrig et al. 2006b). Incompleteness of the theoretical diffusion models in the outer part of the stellar envelope is the most likely explanation for the contradiction between predicted and observed pulsation properties of HgMn stars.

Rapidly oscillating magnetic Ap stars

This section is an updated version of the review published by Kochukhov (2008, in the proceedings of the Wrocław HELAS Workshop "Interpretation of Asteroseismic Data", CoAst, 157, in press).

Rapidly oscillating Ap (roAp) stars represent the most prominent subgroup of pulsating chemically peculiar stars. These objects belong to the SrCrEu type of magnetic A stars, and pulsate in high-overtone, low degree p-modes. roAp stars are found at or near the main sequence, at the cool border of the region occupied by the magnetic Ap/Bp stars (Kochukhov & Bagnulo 2006). According to the series of recent spectroscopic studies (e.g., Ryabchikova et al. 2002, 2004; Kochukhov et al. 2002a), effective temperatures of roAp stars range from about 8100 down to 6400 K. Their atmospheres are characterized by diverse chemical abundance patterns, but typically have normal or below solar concentration of light and iron-peak elements and a very large overabundance of rare-earth elements (REEs). Similar to other cool magnetic A stars, roAp stars possess global fields with a typical strength from few to ten kG (Mathys et al. 1997), although in some stars the field intensity can exceed 20 kG (Kurtz et al. 2006b). These global magnetic topologies are most likely the remnants of the fields which were swept at the star-formation phase or generated by dynamo in the convective envelopes of pre-main sequence stars, then quickly decayed to a stable configuration (Braithwaite & Nordlund 2006) and now remain nearly constant on stellar evolutionary timescales. The slow rotation and stabilizing effect of the strong magnetic field facilitates operation of the atomic diffusion processes (Michaud et al. 1981; LeBlanc & Monin 2004), which are responsible for the grossly non-solar surface chemistry and large element concentration gradients in Ap-star atmospheres (Ryabchikova et al. 2002, 2008; Kochukhov et al. 2006). Variation of the field strength and inclination across the stellar surface alters the local diffusion velocities (Alecian & Stift 2006), leading to the formation of spotted chemical distributions and consequential synchronous rotational modulation of the broad-band photometric indices, spectral line profiles, the longitudinal magnetic field and the mean field modulus (e.g., Ryabchikova et al. 1997).

Pulsations in cool Ap stars were discovered 30 years ago (Kurtz 1978) and were immediately recognized to be another manifestation of the prominent influence of unusually strong magnetic fields on the stellar interiors and atmospheres. Currently, 38 cool Ap stars are known to pulsate. Several new roAp stars were recently discovered using high-resolution spectroscopic observations (Hatzes & Mkrtichian 2004; Elkin et al. 2005; Kurtz et al. 2006b; Kochukhov et al. 2008a, 2009; Gonzáles et al. 2008). Oscillations have amplitudes below 10 mmag in the Johnson's B filter and 0.05–5 km s^{-1} in spectroscopy, while the periods lie in the range from 4 to 22 min. The latter upper period threshold of roAp pulsation corresponds to the second mode recently detected by the high-precision RV observations of the evolved Ap star HD 116114 (Kochukhov, Bagnulo & Lo Curto, in preparation).

The amplitude and phase of pulsational variability are modulated with the stellar rotation. A simple geometrical interpretation of this phenomenon was suggested by the oblique pulsator model of Kurtz (1982), which supposes an alignment of the low angular degree modes with the quasi-dipolar magnetic field of the star and resulting variation of the aspect at which pulsations are seen by the distant observer. Detailed theoretical studies (Bigot & Dziembowski 2002; Saio 2005) showed that the horizontal geometry of p-mode pulsations in magnetic stars is far more complicated: individual modes are distorted by the magnetic field and rotation in such a way that pulsational perturbation cannot be approximated by a single spherical harmonic function.

Photometric studies of roAp pulsations

Majority of roAp stars were discovered by D. Kurtz and collaborators using photometric observations at SAAO (see review by Kurtz & Martinez 2000). The search for roAp stars in the Northern hemisphere is being conducted at the Nainital (Joshi et al. 2006) and Maidanak (Dorokhova & Dorokhov 2005)

observatories. Several roAp stars were observed in coordinated multi-site photometric campaigns (Kurtz et al. 2005a; Handler et al. 2006), which allowed to deduce frequencies with the precision sufficient for asteroseismic analysis. However, low amplitudes of broad-band photometric variation of roAp stars, low duty cycle and aliasing problems inevitably limit precision of the ground-based photometry. Instead of pursuing observations from the ground, recent significant progress has been achieved by uninterrupted, ultra-high precision observations of known roAp stars using small photometric telescopes in space. Here the Canadian MOST space telescope is undisputed leader. The MOST team has completed 3–4 week runs on HD 24712, γ Equ (HD 201601), 10 Aql (HD 176232), HD 134214, and HD 99563. Observations of 33 Lib (HD 137949) are planned for April-May 2009.

In addition to providing unique material for detailed asteroseismic studies of HD 24712, γ Equ, and 10 Aql, the MOST photometry has revealed the presence of a very close frequency pair in γ Equ, giving modulation of pulsation amplitude with ≈18 d period (Huber et al. 2008). It is possible that this frequency beating is responsible for the puzzling discrepancy of the radial velocity amplitudes found for γ Equ in different short spectroscopic observing runs (Sachkov et al. 2009). This amplitude variation could not be ascribed to the rotational modulation because rotation period of this star exceeds 70 years (Bychkov et al. 2006).

Spectroscopy of roAp pulsations

High-quality time-resolved spectra of roAp stars have proven to be the source of new, incredibly rich information, which not only opened new possibilities for the research on magneto-acoustic pulsations but yielded results of wide astrophysical significance. Numerous spectroscopic studies of individual roAp stars (e.g., Kochukhov & Ryabchikova 2001a; Mkrtichian et al. 2003; Ryabchikova et al. 2007a), as well as comprehensive analysis of pulsational variability in 10 roAp stars published by Ryabchikova et al. (2007b), demonstrated pulsations in spectral lines very different from those observed in any other type of non-radially pulsating stars. The most prominent characteristic of the RV oscillation in roAp stars is the extreme diversity of pulsation signatures of different elements. Only a few stars show evidence of $<$50 m s^{-1} variation in the lines of iron-peak elements, whereas REE lines, especially those of Nd II, Nd III, Pr III, Dy III, and Tb III exhibit amplitudes ranging from a few hundred m s^{-1} to several km s^{-1}. The narrow core of Hα behaves similarly to REE lines (Kochukhov 2003; Ryabchikova et al. 2007b), suggesting line formation at comparable atmospheric heights.

Pulsation phase also changes significantly from one line to another (Kochukhov & Ryabchikova 2001a; Mkrtichian et al. 2003), with the most notorious example of 33 Lib where different lines of $the\ same\ ion$ pulsate with a 180° shift in phase, revealing a radial node, and show very different ratios of the amplitude at the main frequency and its first harmonic (Ryabchikova et al. 2007b). Several studies concluded that, in general, roAp stars show a combination of running (changing phase) and standing (constant phase) pulsation waves at different atmospheric heights.

Another unusual aspect of the spectroscopic pulsations in roAp stars is a large change of the oscillation amplitude and phase from the line core to the wings. The bisector variation expected for the regular spherical harmonic oscillation is unremarkable and should exhibit neither changing phase nor significantly varying amplitude. Contrary to this expectation of the common single-layer pulsation model, the roAp bisector amplitude often shows an increase from 200–400 m s^{-1} in the cores of strong REE lines to 2–3 km s^{-1} in the line wings, accompanied by significant changes of the bisector phase (Sachkov et al. 2004; Kurtz et al. 2005b; Ryabchikova et al. 2007b).

The ability to resolve and measure with high precision pulsational variation in individual lines allows to focus analysis on the spectral features most sensitive to pulsations. By co-adding radial velocity curves of many REE lines recorded in a spectrum with a wide wavelength coverage one is able to reach the RV accuracy of $\sim$1 m s^{-1} (Mathys et al. 2007). This made possible discovery of the very low-amplitude oscillations in HD 75445 (Kochukhov et al. 2009) and HD 137909 (Hatzes & Mkrtichian 2004). The second object, well-known cool Ap star β CrB, was previously considered to be a typical non-pulsating Ap (noAp) star due to null results of numerous photometric searches of pulsations (Martinez & Kurtz 1994) and the absence of prominent REE ionization anomaly found for nearly all other roAp stars (Ryabchikova et al. 2001, 2004). The fact that β CrB is revealed as the second brightest roAp star corroborates the idea that p-mode oscillations could be present in all cool Ap stars but low pulsation amplitudes prevented detection of pulsations in the so-called noAp stars (Kochukhov et al. 2002b; Ryabchikova et al. 2004).

Despite the improved sensitivity in searches of the low-amplitude oscillations in roAp candidates and numerous outstanding discoveries for known roAp stars, the major limitation of the high-resolution spectroscopic monitoring is a relatively small amount of observing time available at large telescopes for these projects. As a result, only snapshot time-series spanning 2–4 hours were recorded for most roAp stars, thus providing an incomplete and, possibly, biased picture for the multiperiodic pulsators, for which close frequencies cannot be resolved in such short runs. Observations on different nights, required to infer detailed RV frequency spectrum, were secured only for a few roAp stars (Kochukhov 2006; Mkrtichian

et al. 2008). For example, in recent multi-site spectroscopic campaign carried out for 10 Aql using two telescopes on seven observing nights (Sachkov et al. 2008), we found that beating of the three dominant frequencies leads to strong changes of the apparent RV amplitude during several hours. This phenomenon could explain puzzling modulation of the RV pulsations on timescales of 1–2 hours detected in some roAp stars (Kochukhov & Ryabchikova 2001b; Kurtz et al. 2006a).

Asteroseismology of roAp stars

The question of the roAp excitation mechanism has been debated for many years but now is narrowed down to the κ mechanism acting in the hydrogen ionization zone, with the additional influence from the magnetic quenching of convection and composition gradients built up by the atomic diffusion (Balmforth et al. 2001; Cunha 2002; Vauclair & Théado 2004). However, theories cannot reproduce the observed temperature and luminosity distribution of roAp stars and have not been able to identify parameters distinguishing pulsating Ap stars from their apparently constant, but otherwise very similar, counterparts (Théado et al. 2009). At the same time, some success has been achieved in calculating magnetic perturbation of oscillation frequencies (Cunha & Gough 2000; Saio & Gautschy 2004) and inferring fundamental parameters and interior properties for multiperiodic roAp stars (Matthews et al. 1999; Cunha et al. 2003).

Recent asteroseismic interpretation of the frequencies deduced from the MOST data for γ Equ (Gruberbauer et al. 2008) and 10 Aql (Huber et al. 2008) yields stellar parameters in good agreement with detailed model atmosphere studies. At the same time, the magnetic field required by seismic models to fit the observed frequencies is 2–3 times stronger than the field modulus inferred from the Zeeman split spectral lines. This discrepancy could be an indication that magnetic field in the p-mode driving zone is significantly stronger than the surface field or it may reflect an incompleteness of the theoretical models.

Mkrtichian et al. (2008) presented the first detailed asteroseismic analysis of a roAp star based entirely on spectroscopic observations. Using high-precision RV measurements spanning four consecutive nights, the authors detected 26 frequencies for famous roAp star HD 101065 (Przybylski's star). Mode identification showed the presence of 15 individual modes with $\ell = 0$–2. This rich frequency spectrum of HD 101065 can be well reproduced by theoretical models if an excessively strong (≈ 9 kG) dipolar magnetic field is assumed, in contradiction to $\langle B \rangle = 2.3$ kG inferred directly from the stellar spectrum (Cowley et al. 2000).

Tomography of atmospheric pulsations in roAp stars

The key observational signature of roAp pulsations in spectroscopy – large line-to-line variation of pulsation amplitude and phase – is understood in terms of an interplay between pulsations and chemical stratification. The studies by Ryabchikova et al. (2002, 2008) and Kochukhov et al. (2006) demonstrated that light and iron-peak elements tend to be overabundant in deep atmospheric layers (typically $\log \tau_{5000} \geq -0.5$) of cool Ap stars, which agrees with the predictions of self-consistent diffusion models (LeBlanc & Monin 2004). On the other hand, REEs accumulate in a cloud at very low optical depth. The NLTE stratification studies, performed for Nd and Pr ions, place the lower boundary of this cloud at $\log \tau_{5000} \approx -3$ (Mashonkina et al. 2005, 2009). Then, the rise of pulsation amplitude towards the upper atmospheric layers due to exponential density decrease does not affect Ca, Fe, and Cr lines but shows up prominently in the core of Hα and in REE lines. This picture of the pulsation waves propagating outwards through the stellar atmosphere with highly inhomogeneous chemistry has gained general support from observations and theoretical studies alike. Hence the properties of roAp atmospheres allow an entirely new type of asteroseismic analysis – vertical resolution of p-mode cross-sections simultaneously with the constraints on distribution of chemical abundances.

The two complimentary approaches to the roAp pulsation tomography problem have been discussed by Ryabchikova et al. (2007a, 2007b). On the one hand, tedious and detailed line formation calculations, including stratification analysis, NLTE line formation, sophisticated model atmospheres and polarized radiative transfer, can supply mean formation heights for individual pulsating lines. Then, the pulsation mode structure can be mapped directly by plotting pulsation amplitude and phase of selected lines against optical or geometrical depth. On the other hand, the phase-amplitude diagram method proposed by Ryabchikova et al. (2007b) is suitable for a coarse analysis of the vertical pulsation structure without invoking model atmosphere calculations but assuming the presence of the outwardly propagating wave characterized by a continuous change of amplitude and phase. In this case, a scatter plot of the RV measurements in the phase-amplitude plane can be interpreted in terms of the standing and running waves, propagating in different parts of the atmosphere.

To learn about the physics of roAp atmospheric oscillations one should compare empirical pulsation maps with theoretical models of the p-mode propagation in magnetically-dominant ($\beta << 1$) part of the stellar envelope. Sousa & Cunha (2008) considered an analytical model of the radial modes in an isothermal atmosphere with exponential density decrease. They argue that waves are decoupled into the standing

magnetic and running acoustic components, oriented perpendicular and along the magnetic field lines, respectively. The total projected pulsation velocity, produced by a superposition of these two components, can have widely different vertical profile depending on the magnetic field strength, inclination and the aspect angle. For certain magnetic field parameters and viewing geometries the two components cancel out, creating a node-like structure. This model can possibly account for observations of radial nodes in 33 Lib (Mkrtichian et al. 2003) and 10 Aql (Sachkov et al. 2008).

The question of interpreting the line profile variation (LPV) of roAp stars has recieved great attention after it was demonstrated that the REE lines in γ Equ exhibit unusual blue-to-red asymmetric variation (Kochukhov & Ryabchikova 2001a), which is entirely unexpected for a slowly rotating non-radial pulsator. Kochukhov et al. (2007) showed the presence of similar LPV in the REE lines of several other roAp stars and presented examples of the transformation from the usual symmetric blue-red-blue LPV in Nd II lines to the asymmetric blue-to-red waves in the Pr III and Dy III lines formed higher in the atmosphere. These lines also show anomalously broad profiles (e.g., Ryabchikova et al. 2007b), suggesting existence of an isotropic velocity field, with dispersion of the order of 10 $\mathrm{km\,s^{-1}}$, in the uppermost atmospheric layers. Kochukhov et al. (2007) proposed a phenomenological model of the interaction between this turbulent layer and pulsations that has successfully reproduced asymmetric LPV of doubly ionized REE lines. An alternative model by Shibahashi et al. (2008) obtains similar LPV by postulating formation of REE lines at extremely low optical depths, in disagreement with the detailed NLTE calculations by Mashonkina et al. (2005, 2009), and requires the presence of shock waves in stellar atmospheres, which is impossible to reconcile with the fact that observed RV amplitudes are well below the sound speed.

Oblique pulsations and distortion of non-radial modes by rotation and magnetic field precludes direct application of the standard mode identification techniques to roAp stars. A meaningful study of their horizontal pulsation geometry became possible by using the method of pulsation Doppler imaging (Kochukhov 2004a). This technique derives maps of pulsational fluctuations without making $a\ priori$ assumption of the spherical harmonic pulsation geometry. Application of this method to HR 3831 (Kochukhov 2004b) provided the first independent verification of the oblique pulsator model by showing alignment of the axisymmetric pulsations with the symmetry axis of the stellar magnetic field. At the same time, Saio (2005) showed that the observed deviation of the oscillation geometry of HR 3831 from a oblique dipole mode agrees well with his model of magnetically distorted pulsation.

Outlook

A progress in understanding the relation between the phenomena of chemical peculiarity and stellar pulsations calls for a detailed model atmosphere and chemical abundance analysis of the suspected high-amplitude δ Scuti Ap and classical Am stars. Interpretation of the modern high-resolution spectroscopic observational material using realistic model atmospheres is also needed to clarify the question of the connection between CP and hot pulsating stars. Systematic high-resolution spectropolarimetric observations are urgently needed to verify the claims of weak magnetic fields in many SPB and a few β Cephei stars. On the other hand, comprehensive theoretical modelling is needed to explore asteroseismic potential of the pulsating λ Boo stars and, in particular, to test possibilities of constraining their interior chemical profiles.

For roAp stars, several important open questions and promising research directions can be identified. On the theoretical side, the failure of the current pulsation models to account for the observed blue and red borders of the roAp instability strip should be addressed by including a more realistic physical description of the interplay between pulsations, magnetic fields, stratified chemistry, and stellar rotation. On the observational side, systematic spectroscopic searches for low-amplitude magnetoacoustic oscillations in cool Ap stars are evidently needed to overcome the limitations and biases of previous photometric surveys.

The remarkable spectroscopic pulsational behaviour, demonstrated in numerous recent studies of roAp stars, extends the roAp research to the uncharted territory far beyond the field of classical asteroseismology. In addition to interpretation of pulsation frequencies, roAp stars now offer a unique opportunity for *pulsation tomography*, i.e. a study of different pulsation modes in 3-D, made possible by the rotational modulation of the oblique pulsations and a prominent effect of chemical stratification. Spectacular observational results, such as resolution of the vertical pulsation mode cross-sections and Doppler imaging of atmospheric pulsations in roAp stars, are, however, yet to be matched by corresponding theoretical developments. At the moment we lack realistic models treating propagation of pulsation waves in the outer layers of magnetic Ap stars. Our knowledge about chemical stratification, in particular that of rare-earth elements, and its impact on the atmospheric structure is equally incomplete. Addressing these theoretical questions is required for the development of a solid physical basis for astrophysical interpretation of the recent roAp pulsation tomography results.

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